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AUTHORITY
E.O 10501 dtd 5 Nov 1953 ; ONR ltr 26 Oct 1977

Department of the Navy
Office of Naval Research
[redacted] N6onr-24424
[redacted] NR-230-042

EXPERIMENTAL STUDY OF FROUDE NUMBER MODELING FOR CYLINDERS PLANING ON WATER

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Report No. E-24.4
Jan[redacted]52

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In determining the forces that are of importance in the development of cavity-running projectiles, measurements might be made on the actual prototypes, or models of each specific prototype might be tested under conditions simulating normal operation. Information applicable to a wider range of development problems is provided, however, by breaking the problem down into several parts, such as a study of the cavity itself, of the characteristics of nose shapes under cavity-running conditions, and of the interaction between the afterbody of a missile and the cavity wall. Such data, when accumulated, may be combined or applied piecewise to design problems of the prototype.

The study of the forces acting upon a missile afterbody, when it contacts the cavity wall during underwater flight, requires that valid modeling laws be determined and checked if prototype application is to be kept in mind. When free surfaces are involved, Froude number similarity is of great importance in certain ranges of operation. If the prototype operation is in a range where inertial forces are predominant over those due to gravity, it is expedient to run model tests at a lower Froude number but still high enough to make the inertial forces predominant. In past experiments by other investigators, Froude number modeling has been carried out over a wide range with planing flat plates; but for planing cylinders, the Froude number variation has not been sufficient to establish limiting values above which changes in Froude number produce no detectable change in the ratio of inertial forces to those due to gravity.

It is the purpose of the present investigation to extend the range of Froude number variation on planing cylinders and show where such modeling is highly significant as well as to show the required test conditions to make inertial forces predominant so that there is no detectable further variation in lift coefficient due to increasing the Froude number. The tests were conducted so as to reveal scale effects other than those due to

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Froude number variation, but further investigation is required for complete identification and separation of the effects responsible for the observed variations which were not attributable to Froude number.

Only the lift force was measured because it will contribute the greatest stabilizing effect for relatively long cavity-running projectiles. The cylindrical model is important because it is a frequently used simple shape and because it is representative of missile afterbodies of various axially symmetrical forms. The cylinder is indicated as representative of a family of cones, for instance, by the results of a series of lift measurements[1*] in which cone size and test velocity were chosen on the basis of the present Froude number investigation. It was found that the lift coefficient plotted against the angle of attack of the lowest surface element of the cone was independent of cone angle for differences up to about 30°. Thus, cones up to 30° apex angle produced the same lift coefficient as did cylinders when both were at the same surface angle of attack and submergence-diameter ratio.

Models were made to plane on the flat free surface of the water tunnel instead of on a curved cavity wall in order to simplify the experimental procedure and to provide a limiting case for reference in later studies of the effect of the curvature of the water surface.

Experimental Procedure

The Free-Surface Water Tunnel of the Hydrodynamics Laboratory at the California Institute of Technology was used in these investigations because of the ease with which measurements of forces, model position, and water velocity could be made. Since lift forces are paramount in influencing the performance of relatively slender cavity-running bodies, and since drag forces are more sensitive to scale effect and boundary-layer phenomena, it was considered expedient to investigate the simpler, more important case first. Moment measurements are involved with both lift and drag, so they, too, were postponed.

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*See bibliography at end of this report.

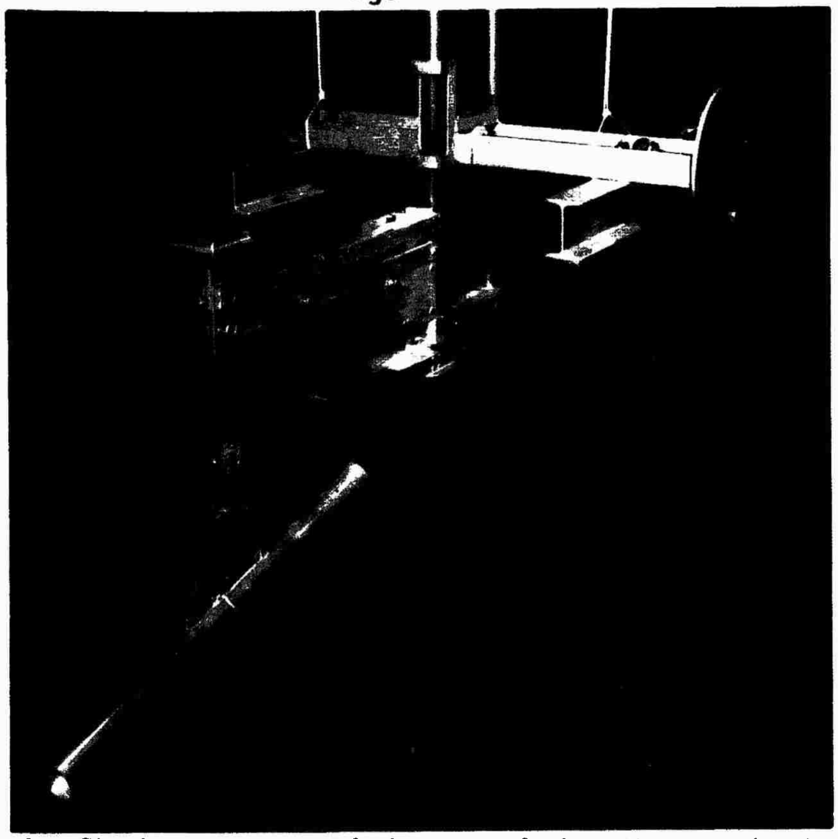

Fig. 1 - Single-component balance and elevating mechanism used to measure lift force on planing cylinders

A single-component, mechanical balance (Fig. 1) was used in making the lift measurements. The procedure used was as follows: A counter mounted on the elevating mechanism was set to read zero at the elevation where the crest of small surface ripples touched the model as often as the trough of the ripples cleared it. When this point of zero submergence was determined, the null-indicating pin was locked in the center of its travel. Weights of known amount were then placed on the balance pan after unlocking the null-indicating pin. By cranking the elevating mechanism downward, the null-indicating pin was again centered and the value of lift force associated with this measured submergence was recorded. After the zero was set for a run, the elevation corresponding to a given load could be repeated to $\pm$ 0.001 ft. Likewise, the zero-submergence setting could be repeated to $\pm$ 0.001 ft., although it is thought that small oscillations of the height of the water level in the tunnel combined with disturbances on the surface of the water make the definition of the zero-submergence point subject to an uncertainty of $\pm$ 0.002 ft.

The tunnel velocity was determined by reading the pressure head on the upstream end of the nozzle and referring to the calibration curve which

had been previously prepared. These readings of velocity are accurate to $\pm$ 1/2%.

The angle of attack was determined by measuring the elevation of two points on the model which were at a known distance apart. This measurement was made using the elevating mechanism itself when the tunnel was filled with water, but not running. A correction amounting to 0° $10'$ of arc was applied because of the slight longitudinal slope of the water surface which is observed when the water is flowing.

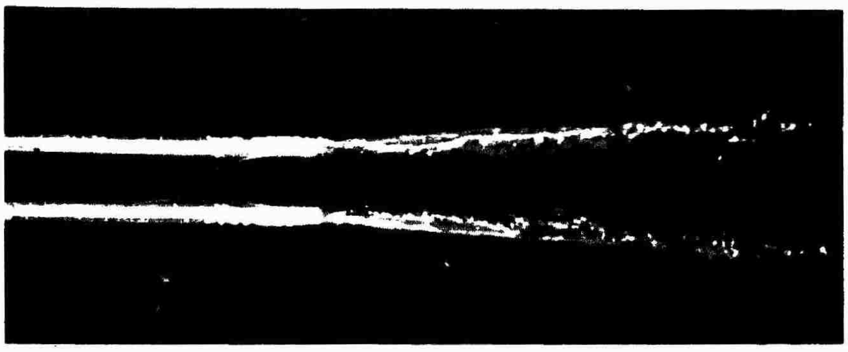

Fig. 2 - Photograph from above of a 2-in. diameter lucite cylinder planing on water
$\alpha = 4.5^{\circ}$ $\delta/d = .125$ $V_0 = 15$ ft/sec

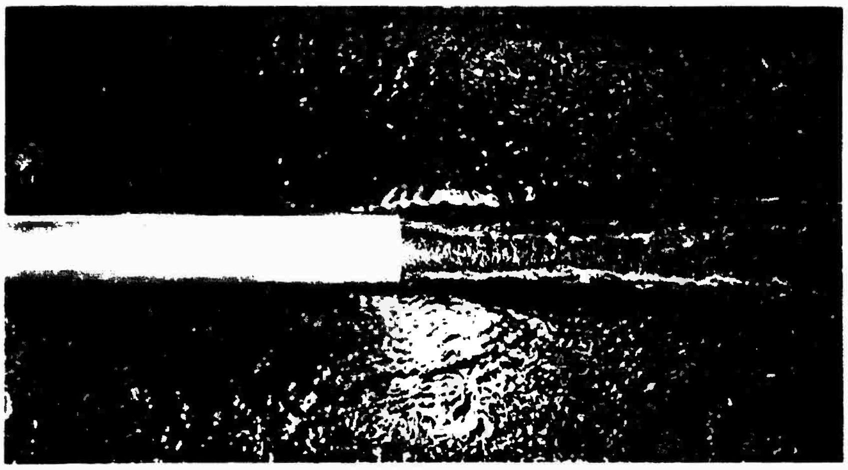

Fig. 3 - Photograph from above of a 2-in. diameter aluminum cylinder planing on water
$\alpha = 4.5^{\circ}$ $\delta/d = .18$ $V_0 = 15$ ft/sec

Hollow lucite cylinders with open ends were originally used as models, since it was considered advantageous to be able to see through the model to study the flow pattern, but these were later abandoned in favor of cylinders made from aluminum tubing when it was found that the lucite cylinders bent under the load when placed in the flow (Figs. 2 and 3). Hollow cylinders

with both ends open were used to alleviate the possibility of introducing varying end forces on the cylinders which would have a component in the direction of the lift force. With a solid cylinder, the magnitude of these end forces would be determined by the pressure in the cavity which trailed from the end of the cylinder at deeper submergence. Not only was it desirable to avoid a change in behavior when a closed cavity was formed, but also the open end cylinder was considered better for an investigation of variations due to Froude number. The cavity pressure behind a solid cylinder is known to be influenced greatly by other scale effects.

Analysis of Data

Since the flow pattern associated with planing is partially bounded by free surfaces so that the influence of gravity can be significant, it was thought that the use of Froude number as a modeling parameter would definitely require investigation and might be sufficient to insure dynamic similarity for models of varying sizes operating at different speeds. In order to check the Froude number modeling criterion while allowing other scale effects to manifest themselves, various model sizes were tested at a range of velocities. Models larger than 2-in. diameter were not used because of the possibility of tunnel blockage effects and because this extended the operation to a Froude number low enough for large scale effects to be present. Models smaller than 2-in. diameter were used to permit other scale effects to be shown as well as to obtain, within the limited range of test velocity available in the Free-Surface Water Tunnel, the higher Froude numbers necessary to make the inertial forces predominant over those due to gravity. Models smaller than 1/2-in. diameter were avoided because submergence measurements were then seriously influenced by the roughness of the water surface. The sizes used allowed duplication, insofar as Froude number effects were concerned, of the results to be expected for high-speed operation of a prototype vehicle.

Figure 4 shows the plotted values of lift coefficient for a typical run in which the pitch angle was held constant and the submergence varied. That scale effects are present is indicated in Fig. 5, where it is seen that different values were obtained as the tunnel velocity was changed. The run at highest velocity in the Free-Surface Water Tunnel (24.4 fps) is seen to approach closely the results of Hogg and Smith[2] which were

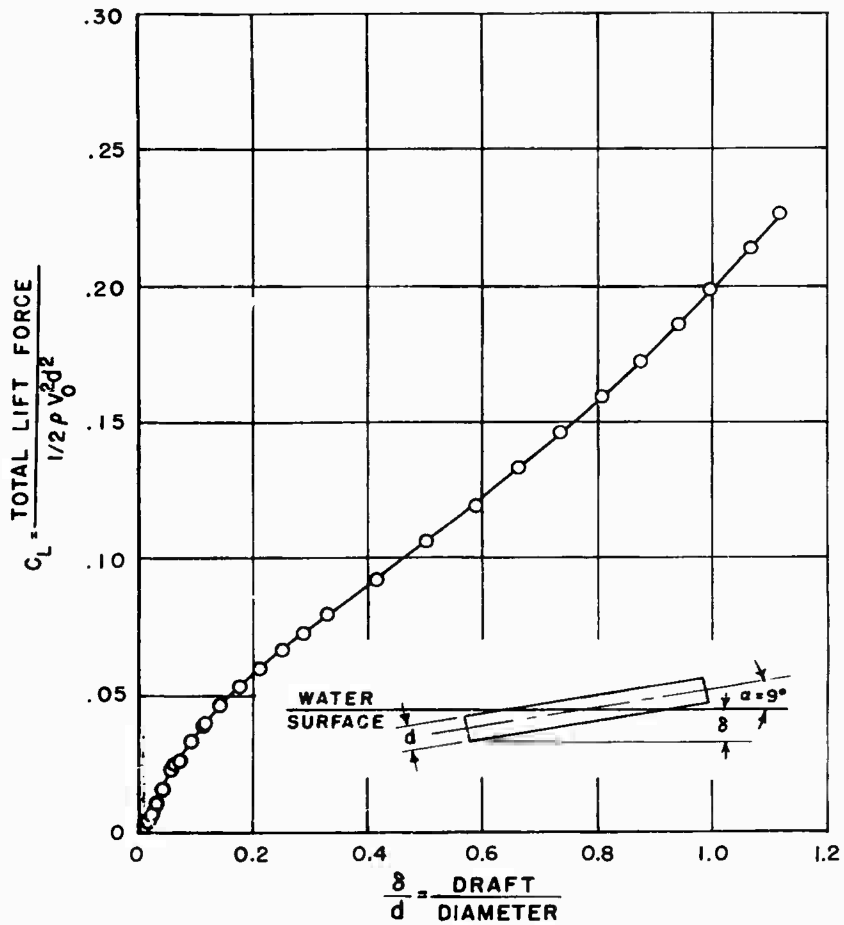

Fig. 4 - Plot of lift coefficient vs. draft-diameter ratio for a hollow 2-in. diameter open-end cylinder planing on water. Angle of attack $\alpha = 9^o$. $V_o = 16.7$ fps. Froude number based on diameter $F_d = V_o/\sqrt{gd} = 7.21$

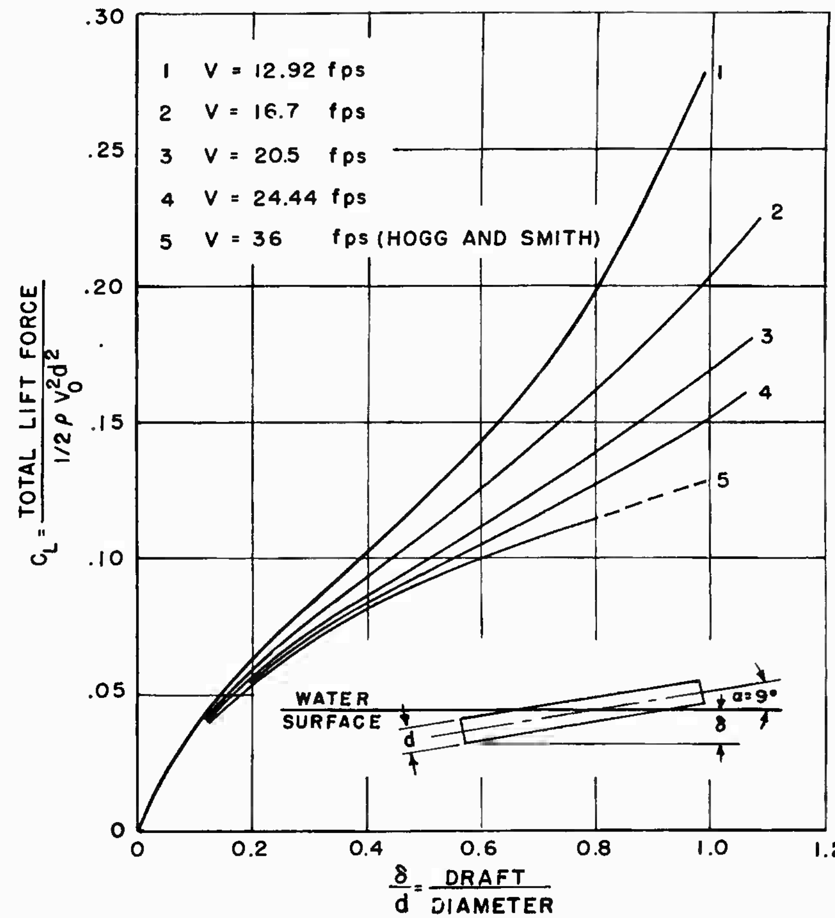

Fig. 5 - Effect of change in velocity on the values of lift coefficient for a 2-in. diameter open-end cylinder planing on water. Angle of attack $\alpha = 9^o$.

reported to be independent of velocity in the range from 30 to 40 fps. It is seen that the present investigation is extended well into the range where scale effects are large.

The lift coefficients for different model sizes and angles of attack operating at a range of velocities, originally plotted as shown in Fig. 4, have been cross-plotted against Froude number for many geometrical flow configurations in Figs. 6, 7, and 8. Systematic variations due to changes in Froude number are evident and are large for some configurations. The curves indicate, by their approach toward a constant lift coefficient, the Froude number necessary to make negligible the effects of gravity as compared to dynamic forces, that is, to simulate high-speed prototype operation in so far as Froude number effects are concerned.

Although the general trend due to Froude number variation is evident, changes in model size often cause discrepancies in lift coefficient for a given geometrical configuration and Froude number. These evidences of other scale effects are present in Fig. 6, for instance. Whereas the results for 1- and 2-in. models are close for all Froude numbers and, at the higher test velocity, these, as well as the results for the half-inch cylinder, approach the values obtained by Hogg and Smith, there is considerable discrepancy due to other scale effects for the half-inch model at low velocity. It is also noted that in Fig. 7 an abrupt drop in the curves is present at a Froude number of 16 or 17. It was thought that small experimental errors might possibly have accounted for the discrepancy, so check runs were made in this region. The results of seven separate trails indicate that a sharp break does occur at a Froude number of 17, and that this break should not be attributed to experimental error. On comparing this break with the systematic variations due to Froude number, it becomes evident that it is due to other scale effects.

For the highest angle of attack (Fig. 8), the results for various model sizes are in close agreement at low submergence but show a tendency, at deeper submergence, for the larger model to have a smaller lift coefficient. Further evidence of other scale effects at this angle of attack is shown by the pronounced lack of agreement with the results of Hogg and Smith, even for the configurations where the present tests are consistent for a given Froude number, and where they appear to be carried to the

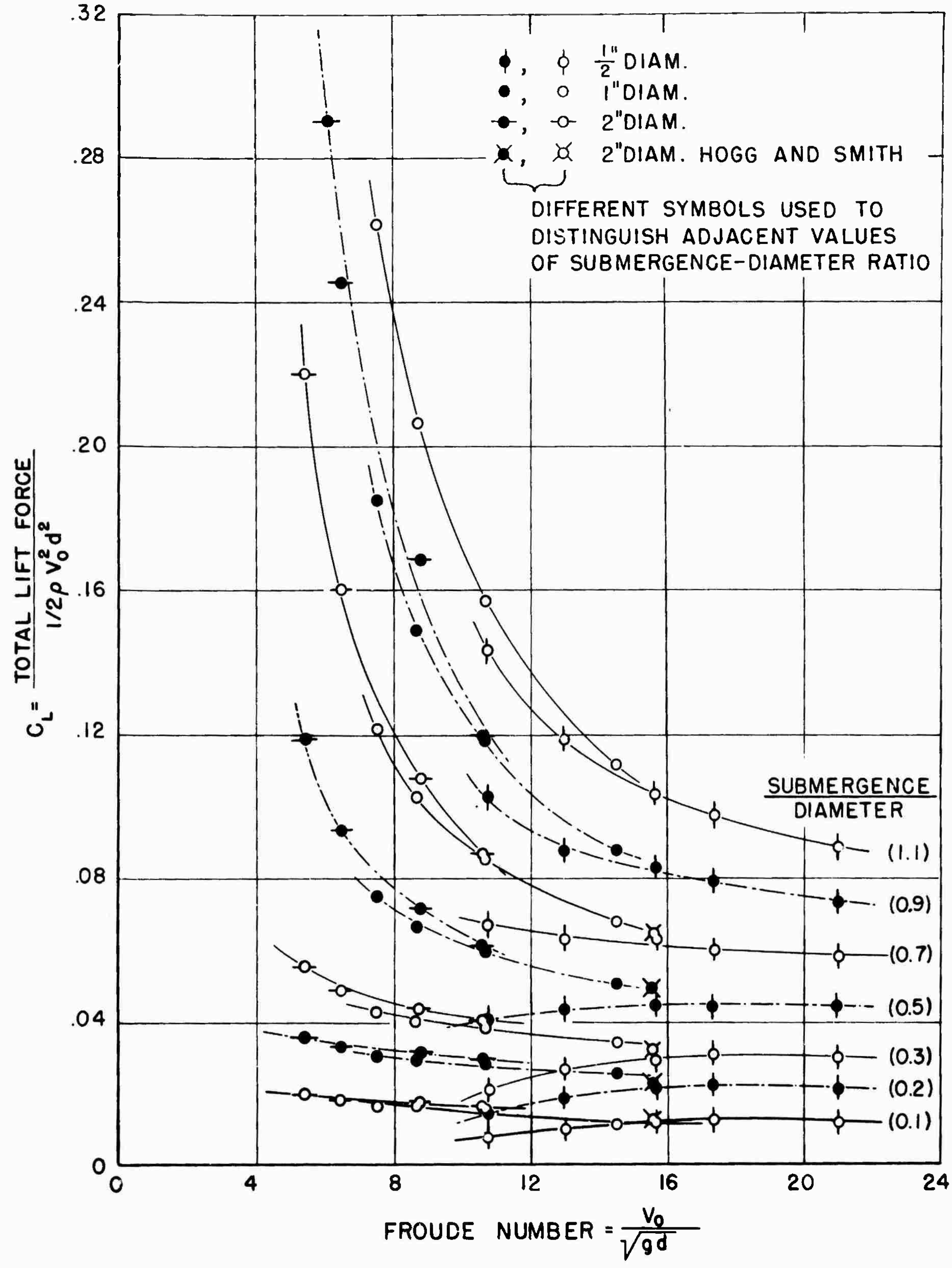

Fig. 6 - Plot of lift coefficient vs. Froude Number for hollow cylinders planing on water. Angle of attack $\alpha = 4.5^\circ$.

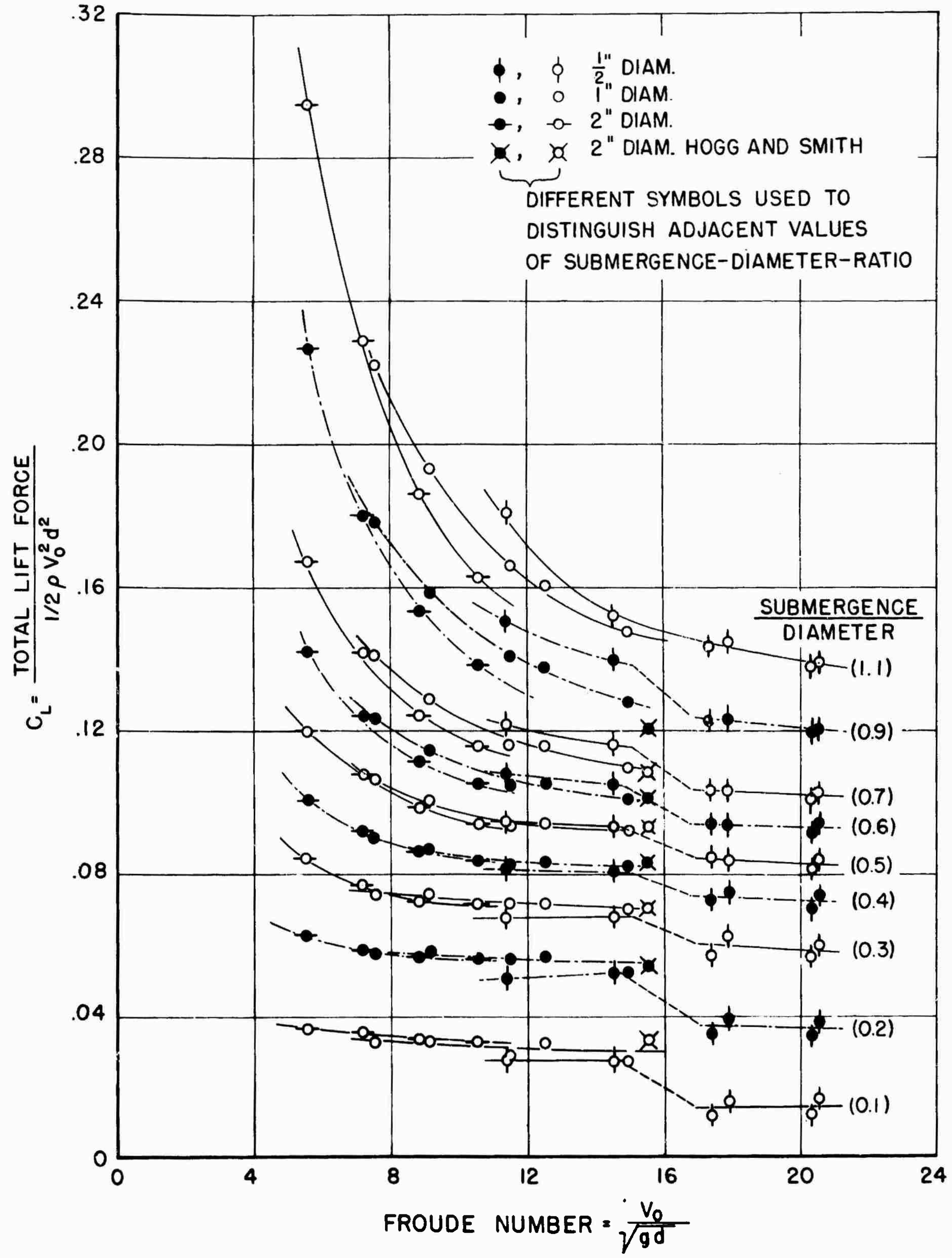

Fig. 7 - Plot of lift coefficient vs. Froude Number for hollow cylinders planing on water. Angle of attack $\alpha = 9^{\circ}$.

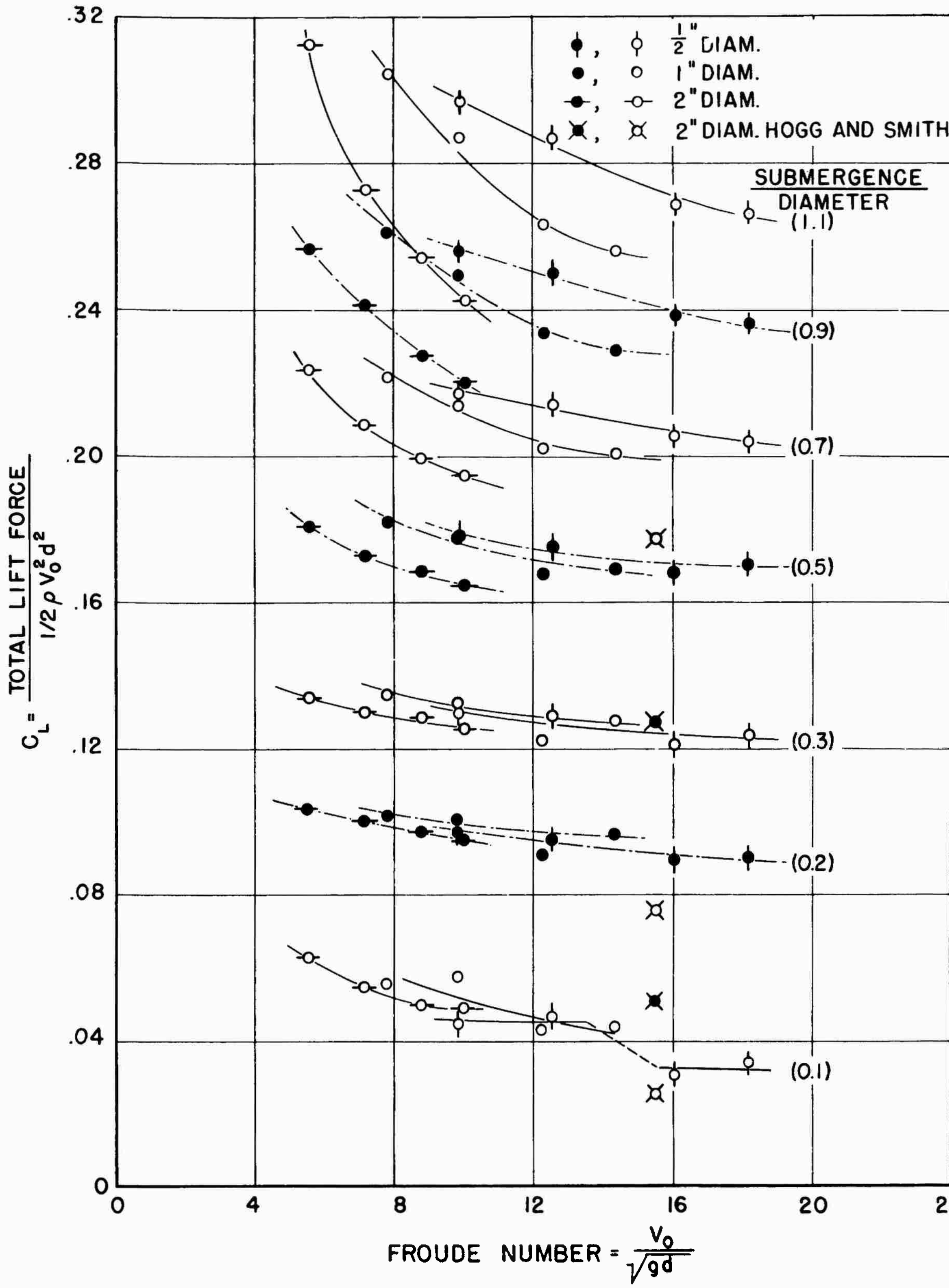

Fig. 8 - Plot of lift coefficient vs. Froude Number for hollow cylinders planing on water. Angle of attack α = 20°.

region of negligible gravity effect. Further consideration of this discrepancy is given in the discussion of results.

Discussion of Results

A visual examination of the flow pattern associated with a hollow cylinder planing on a water surface indicates that there are two regimes of the flow pattern that would appear to be pertinent to the production of forces on the model. These regimes are: (1) the principal depression in the water surface produced by the interference with the oncoming flow, and (2) the spray sheets or blisters that either cling to the model above the line of its intersection with the principal depression or fly off from the model at or above this line. The forces associated with these two regimes might be classified as follows:

(1-a) Normal forces due to the momentum changes resulting from the deflection of the oncoming flow in the formation of the principal depression.

(1-b) Normal hydrostatic forces on the part of the model that is in contact with the water that forms the principal depression.

(1-c) Tangential shear forces due to the motion of the water that forms the principal depression.

(2-a) Normal forces due to momentum changes resulting from the deflection of the oncoming flow in the formation of the spray sheets and from the subsequent deflection of this portion of the flow around and away from the model.

(2-b) Normal hydrostatic forces on the part of the model that is in contact with the water that forms the spray sheets.

(2-c) Tangential shear forces due to the motion of the water that forms the clinging spray sheets.

The first group of forces (1-a, 1-b, and 1-c) is associated with the principal depression, and the second (2-a, 2-b, and 2-c) with the spray.

Qualitative consideration might be given to the relative magnitude of the vertical component of the two groups of forces as well as to the scale effects that would likely be most important in each case. It is universally recognized that the clinging spray sheets formed by a planing cylinder have a large effect on the measured lift force. A study of the two-dimensional, flat planing surface[3] indicates that high angles of attack

produce a large amount of spray having a large vertical velocity component. A large change in lift would occur if scale effects should materially alter the direction of motion of this spray. But for a cylinder planing at a moderate angle of attack, the upward momentum content of the spray is limited. It is unlikely, therefore, that scale effects could result in sufficient change in momentum to produce a change in lift as great as the lift produced in forming the principal depression, but a significant change might be expected.

In the first group of forces that should account for the major portion of the lift, the tangential shear forces (1-c) contribute little in comparison with the inertial forces (1-a). The pressure gradient on the underside of the planing cylinder is such that variations in Reynolds number will not produce noticeable changes in the flow pattern. As a consequence, Reynolds number will be of little significance as a modeling parameter for the first group of forces. It is also noted that, since there is a well-defined separation point at the rear end of the cylinder, surface tension could have little effect and consequently Weber number is not significant. The only pertinent modeling parameter for this group of forces would appera to be Froude number, which determines the relative magnitude of the forces due to gravity (1-b) compared with the inertial forces (1-a).

The similitude conditions are not so simple for the second group of forces associated with the spray. Certainly modeling criteria other than Froude number are significant when the upward vertical velocity component of a clinging spray sheet is reduced or reversed faster than could be accounted for by gravity action. The photographs in Figs. 9 and 10 show different spray patterns obtained when model size and velocity were changed in a way to keep the same Froude number. If these other scale effects are significant at the lower velocities where Froude number modeling is imperative, no exact tests in water with small scale models are possible. At the higher Froude numbers where gravitational forces are small, it may be more important to model some other scale effect. The nature of these other scale effects has not bee determined and their segregation has not been achieved.

It should be noted that the Froude number considerations are of primary importance since they affect both groups of forces, while the other scale effects are pertinent only for the spray. Large gravitational effect

Fig. 9 - 1-in. diameter aluminum cylinder planing at 9^{o},
$\delta/d = 0.1$, $V_{o} = 16.6$ fps,
Froude No. (based on dia.) = 10.13

Fig. 10 - 2-in. diameter aluminum cylinder planing at 9^{o},
$\delta/d = 0.1$, $V_{o} = 23.45$ fps,
Froude No. (based on dia.) = 10.13

is shown, for example, in the present tests where there is a 4 to 1 change in lift for the 4.5° pitch angle at a submergence-diameter ratio of 0.9. On the other hand, the tests for most of the configurations were carried into the range where systematic variation due to changes in Froude number is negligible. It is believed that the test results plotted in Figs. 6, 7, and 8 establish the Froude numbers required to make gravitational forces negligible. Tests at Froude numbers higher than these established limits should not be necessary, in so far as the gravitational action is concerned, but higher velocities and changes in model size might give some further change in lift coefficient due to other scale effects.

The above breakdown of the force system and the discussion of the respective scale effects is believed justified even though the several forces do not result from causes which can be precisely combined to give the total flow picture for the planing cylinder. Because of the presence of the free surface, the geometrical configuration of the boundary of the flow pattern is not fixed, but changes instead in a manner that is dependent upon the combined influence of the various scale effects. A change in Froude number, for example, will result in a different geometrical configuration for the viscous and other forces to act upon. Similarly, the effect of Reynolds number on boundary layers or other flow phenomena may significantly alter the geometrical configuration on which gravity effects are pertinent. But, in spite of these limitations, an analysis of the scale effects on various parts of the force system aids materially in efforts to understand the significance of test data taken under various operating conditions.

It was mentioned previously in the analysis of data, that there is lack of agreement with the results of Hogg and Smith for the case of the highest angle of attack. Since the present tests were carried to Froude numbers even higher than those used by those investigators, it would appear that the difference is due to other scale effects on the spray. The region of agreement, as well as the discrepancy, is shown up more clearly when the data are cross-plotted against angle of attack as shown in Fig. 11. At an angle of about 10°, a sharp drop is present in the lift coefficients of Hogg and Smith, while those determined in this Laboratory show a steady increase with increasing angle of attack. At the lower angles of attack, the more uniform discrepancies which increase with submergence are probably due

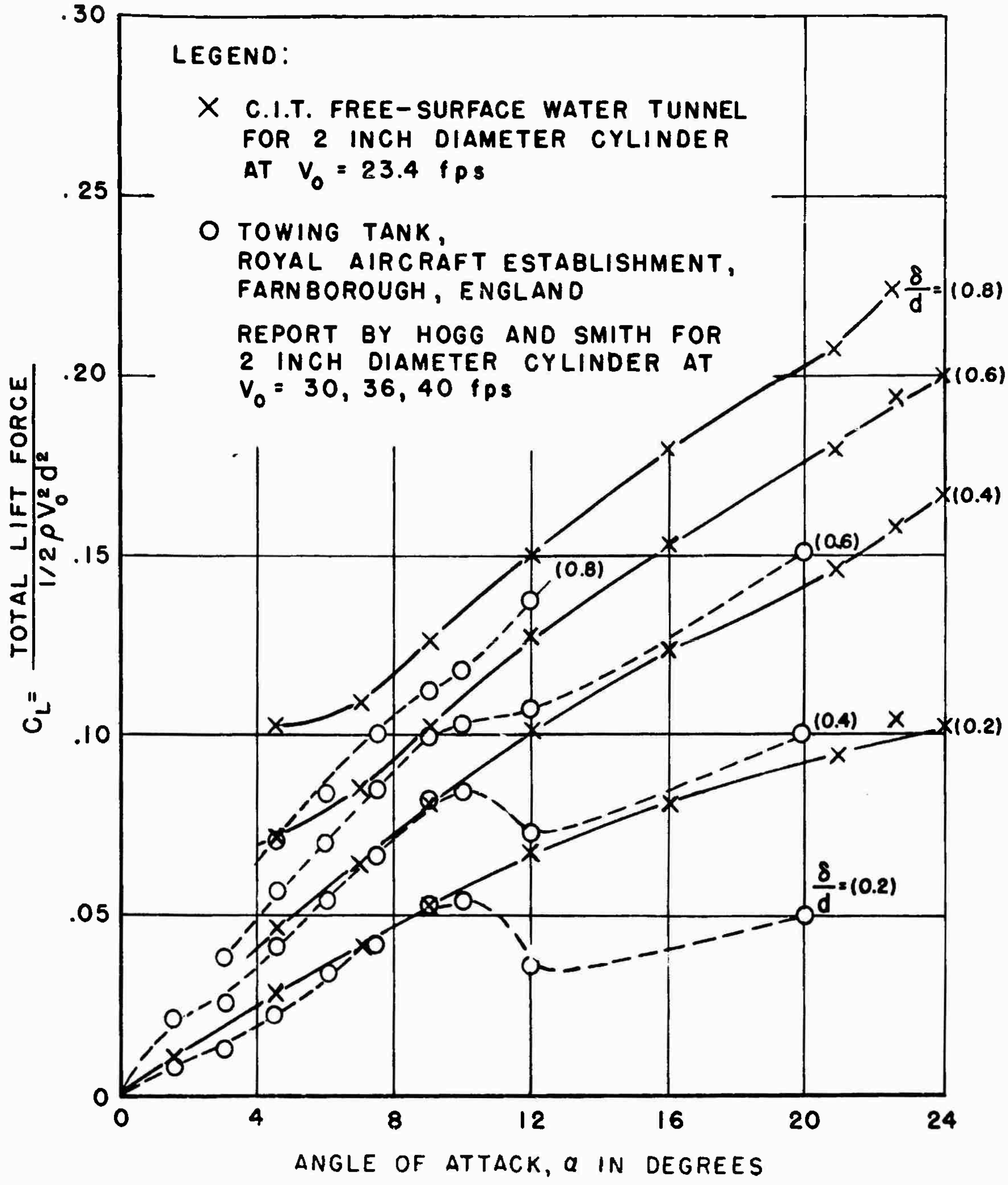

Fig. 11 - Comparison of measured values of lift coefficient plotted against angle of attack for planing cylinders

to Froude number dissimilitude since the behavior observed is to be expected from the nature of the curves showing lift coefficient plotted against Froude number. Hogg and Smith have likened the sharp dip in the lift coefficient curve to the stalling of airfoils completely immersed in the surrounding fluid. Inability to attain velocities greater than 25 fps in the Free-Surface Water Tunnel prevented duplication of the operating conditions of Hogg and Smith so that the exact conditions where the "stall" was reported could not be achieved for experimental study in this Laboratory.

The analysis of the components of the force system on planing cylinders suggests that the discrepancies at the higher angles of attack are due to differences in the action of the spray and are subject to scale effects other than Froude number. The lift coefficient might be expected to change by the order of magnitude shown if, at one velocity, the spray leaves the rear of the model with downward momentum while, at another velocity, it is instead thrown off with an upward trajectory. Hogg and Smith have suggested that the atmospheric pressure provides the forces which cause the film to cling to the model, and that surface tension forces are negligible. Contrary to this, Worthington[4] has shown that, for spheres dropped into water, the clinging of the spray sheet is independent of air pressure but is greatly affected by the adhesion of the liquid to the sphere, and hence by the cleanliness and smoothness of the surface and by the viscosity of the liquid. Further study of the effects of viscosity and surface tension upon the flow of thin water films should provide valuable information applicable to the investigation of planing bodies.

Conclusions

Measurements of the lift coefficient of cylinders planing at various angles of attack and various submergence-diameter ratios have been made to show the variation with Froude number. The results plotted in Figs. 6, 7, and 8 show, by a rapid change in lift coefficient with change in Froude number, the regions where Froude number modeling is definitely necessary. The plots also include regions where there is negligible further systematic change in lift coefficient with increasing Froude number. This indicates that no higher Froude number is required to make the gravitational forces negligible compared to the dynamic forces.

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When the maximum attainable test velocity is limited to 25 fps, as is presently the case with the Free-Surface Water Tunnel, the high-speed operation of a projectile can be approximately simulated in so far as the attainment of gravity-free conditions are concerned, by use of 2-in. diameter models for all but the greatest submergence-diameter ratios, in which case 1-in. diameter models are required to obtain negligible gravity effect. The larger model is preferable wherever Froude number modeling permits because of the greater ease of making force and position measurements.

The use of models smaller than 1-in. diameter has shown evidences of scale effects not yet adequately studied. They should be avoided when Froude number modeling is the criterion because gravity-free operation can be obtained in most cases with larger models and because of the greater difficulty in making force and position measurements.

For other axially symmetrical bodies of revolution, the region of rapid variation in lift coefficient with Froude number might be expected to occur at the same range as indicated for cylinders in Figs. 6, 7, and 8 when comparisons are based on the angle of attack of the lowest surface element of the bodies. This conclusion is supported by considerations of the separate scale effects for various parts of the force system. Experimental indication of its validity was provided in the course of another investigation where cones with up to 30° apex angle gave the same lift coefficient as the cylinder when compared at the same surface angle of attack and submergence-diameter ratio.

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